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UNIVERSITY OF ALBERTA

**BOILING CONTROL DURING WELDING OF LIQUID
FILLED PRESSURIZED PIPE SECTIONS**

BY

RORY BELANGER

**AN EXPERIMENTAL RESEARCH PROJECT
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
AND RESEARCH IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF MASTER OF ENGINEERING**

IN

WELDING ENGINEERING

**DEPARTMENT OF CHEMICAL AND MATERIALS
ENGINEERING**

EDMONTON, ALBERTA

(SPRING, 1997)

THE UNIVERSITY OF CHICAGO

IN THE DEPARTMENT OF THE HISTORY OF ARTS
AND ARCHITECTURE

BY

WILLIAM H. STONE

THE UNIVERSITY OF CHICAGO PRESS
PUBLISHED BY THE UNIVERSITY OF CHICAGO PRESS
CHICAGO, ILL. 60637
AND THE UNIVERSITY OF CHICAGO PRESS
LONDON, ENGLAND

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ABSTRACT

Weld procedure qualification for in-service CSA Z662 oil and gas pipelines in Canada require that test welds be prepared on materials with similar carbon equivalents and that the cooling rate during procedure qualification testing is at least as severe as that encountered on the active pipeline being modeled. A common method of establishing a severe cooling rate during welding on a procedure qualification pipe section involves filling a length of the pipe with flowing water. This method provides a conservative approach to the problem because flowing water will generally provide a weldment cooling rate higher than what is normally encountered on gas pipe lines. This high quench rate has created problems in the qualification of high carbon and carbon equivalent pipelines steels. The ability to control quench rate during qualification testing would serve to lessen the conservatism associated with water filled pipe test sections. Understanding the fluid behavior and controlling this quench rate was the intent of the research work. The experimental research first was focused on evaluating the temperature and fluid behavior at the pipe I.D. during welding. Cooling rate control was then attempted by manipulating fluid properties and pipe section internal pressure.

The liquid behavior at the internal diameter of a pressurized pipe section was monitored during welding. With water as a coolant, it was determined that film boiling could effectively be suppressed with increased pressure. It was observed that the internal diameter (I.D.) temperature could be increased with increased pipe section pressure and that the temperature stayed very close to the saturation temperature (T_{sat}). However, the elevated I.D. pipe temperature and increased volume of heated metal was unable to offset the cooling characteristics of the water within the pipe section. Cooling rate could not be effectively controlled with water as a coolant.



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At low pressures, methanol and ethylene glycol, which possess lower and higher respective saturation temperatures relative to water, were found to be useless as coolants due to those liquids' tendency to exhibit dramatic film boiling behavior. The reason for this is considered primarily related to the lower thermal conductivity of ethylene glycol and lower T_{sat} of methanol relative to water.

A 50% ethylene glycol/water solution used as a coolant was found to slow the cooling rate at the pipe I.D. and O.D. relative to water. The degree of this cooling rate suppression could be controlled by increasing the pipe section pressure. The reason for this was the increased T_{sat} of the ethylene glycol/water solution relative to pure water. The water in the solution did serve to keep film boiling in check while the resulting T_{sat} and I.D. pipe temperature was between that of water and that expected for pure ethylene glycol. A 50% methanol/water solution did not have any effect on the I.D. pipe temperature relative to water. The high thermal conductivity of the water dominated in this case and the only change observed over pure water was that the mixture had a higher propensity for film boiling at low pressures.

The use of ethylene glycol/water solution coolants coupled with increased pipe section pressure was shown to be effective in reducing the weld cooling rate in the test apparatus. The research findings has laid the groundwork for establishing an effective method of controlling cooling rates during the welding of procedure qualifications intended for active gas pipelines.

RELEASE

NAME OF AUTHOR: RORY BELANGER

TITLE OF PROJECT: BOILING CONTROL DURING WELDING OF
LIQUID FILLED PRESSURIZED PIPE
SECTIONS

DEGREE: MASTER OF ENGINEERING

YEAR OF DEGREE: SPRING 1997

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The undersigned certifies that he has read, and recommends to the Faculty of graduate studies and research for acceptance, a research project entitled, BOILING CONTROL DURING WELDING OF LIQUID FILLED PRESSURIZED PIPE SECTIONS by Rory Belanger in partial fulfillment of the requirements for the degree of MASTER OF ENGINEERING in WELDING ENGINEERING.

ACKNOWLEDGMENTS

The writer would like to acknowledge the contributions of a number of people who made the completion of the project and the degree possible. This includes Dr. Barry Patchett for technical guidance and industrial and educational contacts and Ron Peters and Robert Gottschlich of Ludwig and Associates for technical assistance with experimental apparatus. Acknowledgment must also include the staff of Ludwig and Associates for their support and patience during the duration of the degree course work and project.

Special thanks are extended to my tireless laboratory technicians, Patrick and Kiara Belanger, for their help during the course of the experiments and their patience and waiting up for their dad for so many evenings.

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LIST OF SYMBOLS AND ABBREVIATIONS

A.G.A.	American Gas Association
Δt_{8-5}	Time in seconds to cool from 1472 to 932 °F (800 to 500 °C)
EWI	Edison Welding Institute
GTAW	Gas Tungsten Arc Welding
HAZ	Heat Affected Zone
R_{1000}	Cooling Rate in °F/s at 1000 °F
WPS	Weld Procedure Specification
WPQR	Weld Procedure Qualification Record
C_p	Heat Capacity
T_2	Final Temperature
T_1	Initial Temperature
m	Mass
ΔH	Enthalpy Change

1.0 Introduction

Hydrocarbon fluid transmission in Canada is accomplished by numerous main and secondary pipelines. Modern materials used in their fabrication possess state of the art properties with respect to strength, weldability, and resistance to brittle fracture. Because of unforeseen demands for product contained within the pipelines, it is often desirable to install a branch connection on one of these existing pipelines while fluid flow is maintained. This technique is generally accomplished by welding and although not a trivial technical challenge, qualifying procedures and successful welding on modern pipeline material usually does not pose a problem. Older pipelines, however, owe their strength to a large degree to elevated levels of carbon. This can present problems considering common present day approaches to qualification of pipeline procedures. The pipeline welding codes in Canada; (previously CSA Z-184/CSA Z-183) have been consolidated into a single standard CSA Z-662. The intent of this specification is to ensure that the product contained within the pipeline does not impair mechanical properties or fracture resistance of the weldment after field welding has been completed. The approach taken is usually quite conservative due to the significant consequences if a problem arises with a weldment on an active gas pipeline. The preparation of the procedure qualification generally involves welding on a similar or higher carbon equivalent pipe material to establish acceptable welding parameters. CSA Z-662 states in 10.9.2.1.1:

"The welding procedure specification, the weld procedure qualification, and the welder qualification shall be based on a predicted cooling rate of the weldment that would result from the expected line flowing conditions and ambient temperatures."¹

Moving fluid within the pipeline provides for an accelerated rate of heat loss compared to static conditions. For this reason, qualification welding is often performed on a section of pipe which has been filled with flowing water. This will generally provide a much more severe heat sink than would normally be encountered by flowing hydrocarbon gases or liquids. High heat affected zone (HAZ) hardness is not tolerable due to the susceptibility of these areas to cold and corrosion assisted cracking mechanisms. The idea behind the weld qualification on the cold water filled pipe is, of course, that if the procedure can be tailored to work on a highly quenched piece of pipe of similar chemistry, there will be no problem having an acceptable weld on a less severely quenched material.

A problem arises when an existing pipe requires hot tapping which has significant levels of carbon or elevated carbon equivalent. Due to high quench rates associated with the water filled pipe, it is sometimes extremely difficult to find an acceptable weld parameter set or technique which results in an acceptable HAZ hardness on the pipe section and at the same time, does not pose considerable risk of burning through the pipe wall. In this case, the method adopted is to take the line out of service for a time to permit welding without a flowing fluid (coolant). This allows legitimate qualification on a gas filled dry pipe section which will have similar thermal quench characteristics to that expected on the pipeline.

1.1 Project

The intent of the project was to determine if it is practical to lower the cooling rate within pressurized weld pipe sections in a controlled manor. Achieving this would mitigate problems associated with excessively high quench rates on water-filled pipe sections. Originally, a great deal of this project was to be centered around the Battelle/Edison Welding Institute's computer program which is often referred to as the "Battelle Hot

Tap Program." This software was written for, and marketed by, the American Gas Association (A.G.A.). Its intended use is for the prediction of critical cooling rates and temperatures during hot tap welding on pressurized pipelines. The efforts were to be centered around validating the predictions made by the Battelle software which indicated that as pressure is increased on a pipe filled with water, elevated temperatures could be reached on the I.D. of the pipe wall thereby allowing the volume of weld and heated metal to increase significantly.

Discussions with EWI Engineering personnel who have worked extensively in the area of hot tapping and welding on active gas transmission lines, indicated two significant problems in undertaking the originally proposed research. Firstly, the two authors of the software are no longer able to be reached, with one author deceased and the other officially retired. In addition, research done by NOVA and EWI on gas pipelines suggest that the results predicted by the Battelle program were only really valid for a fairly small range of pipe wall thicknesses.²

The research undertaken in this project centers around understanding how heat is transferred from the I.D. wall of a pipe into liquid within a pressurized pipe section. The work performed was to be purely experimental and was originally to employ only water as a pipe section coolant. After initial test results, liquids and mixtures of liquids which had differing fluid properties were used as coolants. Developing a better understanding of how heat transfer is influenced by varying fluid properties and by increased pipe section pressure, would serve to accomplish the original intent of controlling the quench rate on the pipe as well as providing a greater understanding to the type of heat removal.

2.0 Experimental Method

To accomplish the Project Intent outlined in 1.1, the behavior of the liquid and the cooling rate was to be determined on the I.D. of the pressurized pipe section during welding. In addition, cooling rates were also to be established at the pipe O.D. for certain conditions. Pipe I.D. temperatures were established with the use of thermocouples welded to the pipe I.D., while O.D. temperatures and cooling rates were established by use of optical pyrometry.

The welding was conducted in autogenous fashion with a gas tungsten arc (GTAW) process. Travel of the GTAW torch was performed and maintained consistent by a semi-automatic rail mounted flame cutting machine.

Various types of cooling liquids were employed within the pressurized pipe section. These included water, ethylene glycol, ethylene glycol/water mixtures, and methanol/water mixtures. All data was gathered with a two channel digital strip chart recorder. The following are the details of the experimental apparatus and method:

2.1 Pressurized Pipe Section Assembly

The pressure pipe section assembly was made up of a section of 4" Sch. 40 steel pipe 6" long encapsulated with machined cylinder heads (Figure 1). Several of these pipe sections were assembled as multiple passes of the GTAW torch resulted in the pipe section becoming apple core shaped and a general thickening of the pipe wall on the weld path. The material chosen was ASTM A 106 Gr. B pipe. Originally, this grade of material was selected because it generally has a relatively high carbon content similar to older pipeline steels which achieved their strength with carbon as the principle alloying element. The two cylinder heads were machined from 6" alloy steel bar stock. Gasket grooves were machined into the heads to locate gaskets and prevent any movement from the gasket material under pressure and heat. Three sections of 1/2" threaded rod were used to clamp the heads about the pipe section.

Later, during higher pressure testing, the diameters of these rods were increased to 5/8" when yielding was observed.

The modified design is capable of operation to a pressure of 1000 psi. A working drawing of the pipe section assembly design is included in Appendix B. Four gasket materials were used in an attempt to seal the capsule during welding. These included neoprene rubber, vinyl, silicon gasket compound, and standard resin impregnated gasket papers. The latter was found to be the only material which would not extrude or be affected by elevated temperatures at high pressure.

Thermocouple wire was routed through 1/4" NPT brass plugs which had been counter drilled from the inside (small end) and the wires were sealed with epoxy resin. No leakage was encountered with any of these wire/plug assemblies with the exception of one which was damaged as a result of a heat excursion. Pressure testing of the plugs at room temperature was successful to 4,000 psi.

The fluid exit port was positioned as close to the gasket slot as possible on the heads to facilitate total gas evacuation prior to pressurization.

2.2 Welding Machine & Processes

The power supply used during the course of welding was a Miller Gold Star 400SS. The welding was conducted with a gas tungsten arc process (GTAW) with an electrode negative polarity and all welding was accomplished with pure argon shielding gas with a gas flow rate maintained at 30 l/min. The 2% thoriated electrode employed in welding had a 1/8" diameter and the electrodes were dressed by grinding after every second or third pass to maintain a consistent arc during the course of testing. The welding travel was maintained at a constant 4" per minute travel speed with a Gullco GK-171-36 track-mounted cutter crawler (Figure 2). All weld

parameter measurements were conducted at the torch with a Klaise SK-7700 digital amp/volt meter.

2.3 Instrumentation & Measurement

2.3.1 Thermocouples

Type K thermocouples were used throughout the course of testing. The wire diameter chosen was 0.02" and bead fusion was accomplished with the use of an oxyacetylene torch. The beads were flattened to a thickness on the order of 0.025 - 0.030" and were then sanded to remove surface oxides. The flattened thermocouple beads were spot welded to the pipe section I.D. along the anticipated path of the weld progression. Two thermocouples were located on the weld paths of each pipe section for validation and redundancy. Each of these were located 0.25" off center of the pipe section length on a line scribed along the longitudinal axis on the pipe I.D. (Figure 3)

2.3.2 Thermocouple Millivolt Measurements

Thermocouple millivolt measurements were performed with a Kipp & Zown digital strip chart recorder. This provided for two channel recordings of the thermocouple outputs located on the weld line thereby verifying accurate locating of the thermocouples and providing redundancy in the case of a thermocouple failure. This instrument was also used to record the analog output from the optical pyrometer employed for O.D. pipe temperature measurements.

2.3.3 Optical Pyrometry

An Optitherm, Series 12-8700 infrared thermometer was employed in monitoring the O.D. pipe temperature (Figure 4). Calibration for the system was accomplished by heating a small piece of the pipe steel which had a K type thermocouple fused to its surface. Since the use of the pyrometer was for cooling -rate determinations ($\Delta t_{8.5}$), thermal emissivity calibration was conducted at 800°C.

2.4 Pressure System

Elevated pressures were delivered to the pressure pipe section with a Haskell pneumatic hydraulic pump. The pressure was initially monitored with a 0-1000 psi. gauge mounted on the vessel but later was attached to the pump. Initially, the pressure was monitored on the fly. That is, measurement of the pressure within the vessel was monitored by a lab technician during welding (Figure 5) and these readings were relayed to the writer at that instant. The readings were written on the strip chart recorder directly adjacent to the respective millivolt trace. This was necessary as the pressure increased substantially during the course of testing due to water expansion and the very small amount of water contained within the vessel. This proved to be prohibitively difficult with the methanol and glycol runs because of the significantly higher pressure rise encountered with these compounds relative to water. In an attempt to control the pressure rise, a pressure regulator valve was installed on the vessel to bleed liquid at a constant pre-set pressure.

3.0 Testing & Results

3.1 Pressure vs. I.D. Pipe Temperature

Groups of pressurized runs were conducted at specific heat inputs to establish the relationship between fluid pressure and the temperature achieved at the pipe I.D.

immediately adjacent to the weld arc. During these initial runs, it was realized that additional data during testing was available as an increase in pressure occurred between the time the arc crossed between the two thermocouple locations. This increase was found to be considerably higher during testing with the methanol/water and ethanol/glycol mixtures.

3.1.1 Pure Water

With pure water, pressure vs. I.D. pipe temperature testing was conducted with two different heat inputs. These included 27 kJ/in. and 43 kJ/in. This data is presented as Plots 1 and 2 in Plot Section 8. Samples of the strip chart data employed to prepare those plots are presented in Appendix A as A_1 .

3.1.2 Ethylene Glycol

Pure ethylene glycol testing was also attempted. Only one run was conducted with ethylene glycol due to the dramatic film boiling response with this fluid even at very low heat inputs. A copy of the I.D. temperature response curve of pure Ethylene Glycol at a heat input of 35 kJ/in. is presented in Appendix A as A_2 .

Pressure vs. I.D. temperature with a 50% ethylene glycol/water mixture was conducted with heat inputs of 35 kJ/in. and 50 kJ/in.. Two high heat input runs at 65 kJ/in. were also conducted to establish whether a boiling regime change could be promoted at elevated pressures. Pressure regulation was employed with the 50 kJ/in. runs. This data is presented as Plots 3 and 4 in Plot Section 8. Samples of the strip chart data employed to prepare those plots are presented in Appendix A as A_3 .

3.1.3 Methanol

To establish the effect on the I.D. pipe temperature of a fluid with a boiling point lower than that of water, methanol was employed as a coolant. Because pure methanol provides a problem with flammability, it was decided to test a 50% methanol/water mixture for safety reasons. It was determined that the 50% methanol mixture had a very high propensity for film boiling except at elevated pressures. The strip chart illustrating this film boiling tendency is included in Appendix A as A₄. In addition, no signs of I.D. pipe wall temperature increase were detected over that observed with pure water (Plot 5 vs. Plot 2). For this reason, no further testing was performed with methanol solutions.

3.2 Cooling Rates

Cooling rates were determined on both the I.D. and O.D. of the pressurized pipe section with water and with 50% ethylene glycol/water mixtures.

3.2.1 I.D. Pipe Cooling Rates

The I.D. pipe cooling rate was established by evaluating the temperature change over the first five seconds of strip chart movement after nucleate boiling had ceased (see boiling explanation in Discussion). Evaluating when nucleate boiling was occurring was based on the presence of rapid fluctuations in the millivolt vs. time plots on the strip chart recorder during welding (see strip chart data in Appendix A). This analysis was conducted on the strip chart data from the pure water I.D. temperature plots conducted at 42 kJ/in and on 50% ethylene glycol/water I.D. pipe temperature plots with welding conducted at 35 and 50 kJ/in. The results from these analysis were compiled and plotted in the form of cooling rates vs. pressure plots. (Plots 6,7, & 8).

No cooling rate determinations were conducted on the methanol solutions for the same reasons outlined in 3.1.3. Additional discouragement to this testing presented itself when it was discovered that a 50% methanol/water solution will quite nicely support open air combustion.

3.2.2 O.D. Cooling Rates

O.D. cooling rate determinations were conducted with pure water and with a 50% ethylene glycol/water mixture. Heat inputs in the order of 35 kJ/in. were used on the O.D. cooling rate determinations.

Due to the difficulty encountered in set up and calibration of the optical pyrometer and maintaining a constant pressure within the pipe section, a limited number of test runs were conducted. The optical pyrometer employed in testing had limitations due to its relatively large focal spot size (approx. 0.2" at a lens to work piece distance of about 7") requiring that the instrument be located very close to the pipe section. Because the weld zone created by the GTAW torch was view obscured by the torch gas cup, both the torch and the pyrometer camera had to be angled at about 15° relative to the weld axis normal.

Since the relatively high temperature of the O.D. weld metal could be measured after the torch exited the pyrometer focal spot, it was possible to determine the time in seconds for the temperature to fall from 800 to 500°C (Δt_{8-5}). This was accomplished by monitoring the pyrometer analog output with the digital strip chart recorder. The time in seconds required for cooling rate calculation was evaluated from the constant strip chart recorder speed. The cooling rate in °F per second (R_{1000}) was also determined by evaluating the slope of the strip chart plot at 1,000°F for

the respective runs. Plots of $\Delta t_{8.5}$ and R_{1000} at various pressures for the water and the 50% glycol/water mixture are presented in Plots 9 and 10. Samples of strip chart data used to prepare those plots are included in Appendix A as A_5 and A_6 .

4.0 Discussion

When an inadvertent non-continuous arc is applied to a cold piece of steel, exceptionally high cooling rates can be realized. This is referred to as an arc-strike and with this situation in mind, increasing the volume of heated metal should facilitate to slow the cooling rate when welding on liquid-filled pressurized piping. The work conducted by Battelle indicates that, at a constant minimum level of heat input, increasing a water filled pipe section pressure will result in a rapid increase in I.D. pipe temperature and a lowering of the weld cooling rate. Plot 11 illustrates the Hot Tap Program data output from the Battelle model with varying heat inputs and suggests that at a given set of weld parameters, even fairly low heat inputs in the order of 27.5 kJ/inch may force a transition of boiling regime from nucleate to film boiling.

Essentially, the weld zone can be equated to a small hole through which heat is being forced. As the heat transfer being forced through an area is increased to a threshold value, vapor bubbles form at the I.D. surface. It is the critical relationship between pressure, wall and liquid film temperatures, and the various liquid and vapor fluid properties which control the occurrence and stability of vapor bubble formation or nucleate boiling. If a critical level of this heat flux is reached, relative to the fluid conditions and properties, the surface of the I.D. is covered by a vapor film and the temperature rises dramatically as liquid wetting of the pipe surface no longer occurs.

This is the condition predicted by the Battelle model as a rapid jump in I.D. wall temperature and is referred to as film boiling.

4.1 Boiling Suppression And I.D. Pipe Temperature

What actually happens at the pipe I.D., is less dramatic but still very interesting. With water as a cooling medium, the I.D. pipe temperature indeed does rise with pressure but no dramatic point increase indicating film boiling was observed except at atmospheric pressure with moderately high heat inputs. For pure water, the temperature of the pipe I.D. shadows the saturation temperature (T_{sat}) very closely (Plots 1 & 2). At moderate pressures with water as a coolant, the I.D. temperature trace on the strip charts, follows a relatively flat line until the arc passes by the thermocouple. During this plateau zone, bubble development in the area of the thermocouple results in small rapid fluctuations in temperature. The behavior of the fluid about the thermocouple at this point is referred to as nucleate boiling. During this boiling regime, bubbles form on the surface and then are expelled from the surface. This bubble expulsion results in substantial agitation of the surrounding fluid and increases the quench severity.

At a heat input of 42 kJ/in., the adherence to T_{sat} became erratic at low pressures which clearly indicates the onset of film boiling. Demonstration of this boiling transition is illustrated on strip-chart output presented in Appendix A as A₁. As a peak temperature was reached, the boiling became more erratic but there existed not enough energy transfer to develop full film boiling and to permit rapid temperature rise.

At higher pressures, the temperature trace was similar but the temperature fluctuations observed during the plateau region were smaller. In addition, the peak observed when the torch passed directly over the thermocouple locations at low pressures became very insignificant at elevated pressures. Since the pipe wall was at

the T_{sat} , it must be concluded that with water, film boiling can be dramatically suppressed by elevating pipe section pressure. At low pressures, this agrees with the Battelle Model data. However, no dramatic rise in I.D. pipe temperature was observed during testing, even at high pressures with very high heat inputs.

A very interesting observation was that any significant increase in pressure promoted a decrease in transitional or film boiling tendency. That is, the peak temperature which was observed as the torch passed directly adjacent to the thermocouple was suppressed (See Appendix A as A_1). This may help to explain the observations made by a number of welding engineers and technologists when conducting PQR testing on full size water filled pipe specimens. It has been noticed that very small amount of water flow through those pipe specimens tended to prevent the area of metal around the weld from significantly increasing in temperature.⁵ A common assumption is that the water flow was removing the heat purely by thermal mass transfer. It is possible that the reason for elevated temperatures observed was that line pressure had been applied to the pipe section accompanying that water flow thereby preventing film boiling as this pressure could be as high as 80-100 psi.

4.2 Effect of Saturation Temperature on I.D. Pipe Temperature During Welding

Although water provided interesting test results illustrating an I.D. temperature closely shadowing T_{sat} during welding, the pressure required to elevate the I.D. temperature was determined as being excessively high for use in preparation of PQR pipe sections. The water coolant was therefore diluted with a higher and lower boiling point liquids.

Initial testing was conducted with pure ethylene glycol but it was determined that even at fairly significant pressures, film boiling readily occurred. In an attempt to disrupt the film boiling tendency, ethylene glycol was diluted 50% by volume with water.

Testing revealed that the net effect was to increase the I.D. pipe temperature significantly at any given pressure (Plots 3 and 4). Although a positive effect of the addition of ethylene glycol to water was realized, the reason for this observation was not. It was not understood and literature was not available to enable determining whether the temperature elevation at the I.D. pipe wall was due to lower thermal conductivity or higher T_{sat} of the mixture.⁶

To evaluate which was the dominant factor, a coolant mixture was prepared which had a significantly lower T_{sat} but similar thermal conductivity.⁷ The coolant chosen for testing was a 50% by volume methanol/water mixture. It was observed during welding with the methanol/water solution, that the I.D. pipe wall very easily achieved a film boiling condition at low pressures and a very close I.D. pipe-temperature correlation to T_{sat} for water. Since the thermal conductivity of the glycol/water and methanol/water solutions were similar, it was concluded that I.D. pipe temperature increase was dominated by increasing the mixture saturation temperature.

4.3 Pipe I.D. Cooling Rates

To evaluate the influence of pressure on the cooling rate at the pipe I.D., a review of the strip chart data derived from previously determined I.D. pipe-temperature time plots was conducted.

4.3.1 I.D. Cooling Rates With Water

It was observed that, in contrast to the previously stated theory that a greater pressure should deliver a slower cooling rate, an actual increase in post nucleate (immediately after cessation of nucleate boiling) cooling rate was observed. It should be understood that at higher pressures there exists a higher ΔT (temperature differential) between the I.D. pipe temperature and both the bulk water and the pipe temperatures. Plot 7 illustrates clearly that with water as a coolant, as the pressure increases, so

does the post nucleate cooling rate. It is reasoned that, as pressure increases, nucleate bubbles become smaller and the interruption of wetting is less relative to large bubbles. Although the bubbles are smaller, they are still forming (plateau region) and are being expelled from the I.D. metal surface accelerating the convective heat transfer. This, in turn, promotes an accelerated cooling rate. This conclusion is based on the observation that as the pressure increased during welding on all of the liquid-filled pipe sections, the magnitude of the rapid temperature fluctuations associated with nucleate boiling was decreased.

4.3.2 I.D. Cooling Rate With 50% Ethylene Glycol/Water Mixtures

Plot 8 illustrates the plot of post nucleate cooling rate vs. pressure. with a heat input of 35 kJ/in. Except for a low pressure run where transition boiling had obviously occurred, a decreased cooling rate with chamber pressure was observed. The higher saturation temperature and lower coefficient of thermal conductivity of the ethylene glycol mixture was clearly of benefit to decreasing the cooling rate relative to pure water (Plot 8 vs. Plot 7).

With the same testing conducted at 50 kJ/in., the result was a substantially flattened cooling rate vs. pressure curve (Plot 9). The extra volume of melted metal promoted by the higher heat input did serve to slow the cooling rate at the pipe I.D.

4.4 O.D. Cooling Rate Determination

O.D. cooling rate determinations were conducted on the pressurized pipe section assembly with both the ethylene glycol/water mixture and with pure water as coolants. The cooling characteristics were determined in two forms. These included

the time to cool from 1472 to 932 °F (Δt_{8-5})(800°C to 500°C) and the cooling rate at 1,000°F (R_{1000}).

4.4.1 O.D. Cooling Rate with Water

The response of the cooling rate to increase in pressure was minimal with water as a coolant. The R_{1000} response was a slight decrease in the order of about 10% (260 to 230°F/s) with a pressure increase from 80 to 750 psi. The Δt_{8-5} exhibited a similarly slight response with an increase in the order of 28% (1.85 to 2.3s) with the same pressure increase. Plot 9 clearly illustrates that the effect of larger heated metal volume promoted by increased I.D. pipe wall temperature, will not offset the increase in heat transfer resulting from higher pressure (minimized nucleate boiling).

4.4.2 O.D. Cooling Rate with 50% Ethylene Glycol/Water Mixture

In contrast to the results observed with water as a coolant, the response of O.D. cooling rate to increased pressure with ethylene glycol/water mixtures was more positive. The effect of increasing the pressure from 80 to 750 psi was to increase the Δt_{8-5} by about 42% (2.65 to 3.75s) and to decrease the R_{1000} in the order of about 35% (250 to 162.5°F/s). Plot 10 illustrates the increase in Δt_{8-5} with the corresponding decrease in R_{1000} .

5.0 Usefulness of Experimental Results for the Preparation of WPQR's

5.1 Water

The remarkable cooling characteristics of water limit the ability to control pipe wall cooling rate in pressurized pipe sections regardless of pressure. Although higher I.D. pipe temperatures can be forced with increased

pressure, relatively constant cooling rates observed. These observations indicate an increase in heat transfer rate due to boiling suppression which in turn offsets the effect of increased temperature of heated and weld metal.

5.2 Mixtures

The use of a 50% mixture of ethylene glycol and water was effective in slowing cooling rate and may present a useful and predictable method of establishing a less conservative method of preparing WPQR test pipe sections for active gas pipelines. The results of this experimental research indicated that the addition of a higher boiling point, lower thermally conductive, miscible fluid such as ethylene glycol to water for use as a pipe section coolant can serve to promote a controlled increase of the I.D. pipe temperature and lower the O.D. cooling rate. Understanding that the increased T_{sat} of the fluid coupled with lower thermal conductivity does promote a slower cooling rate suggests that a higher boiling point glycol solution will probably allow even slower cooling rates if that is desired. Diethylene glycol, for example has a lower thermal conductivity and a higher boiling point and should therefore be useful in further research.

6.0 Limitations of Project Research and Further Work Necessary

There are number of limitations in the experimental apparatus and methodology which should be addressed before employing glycol based coolants for the preparation of WPQR's.

All of the research conclusions were based on observations of selected manipulated variables or properties. One property which have not been properly addressed. For

example; the influence of viscosity on the ethylene glycol/water heat transfer has not been evaluated. A more thorough literature search and possibly more experimental research will be needed to establish if solution viscosity influences weld cooling rate.

No correlation to actual cooling rates on active gas pipelines have been attempted. Although Δt_{8-5} values on active gas pipelines have been documented by both Battelle and EWI, these values were based on the SMAW process.^{3,8} Trying to correlate Δt_{8-5} from the pipe section to those results would be premature without a better understanding of the correlation of process heat inputs.

Conspicuously left out of the project work was a determination of the heat input relationship between the SMAW and GTAW processes. Although a few arc efficiency evaluations and correlations exist, the significant influence of the process variables make application of these values questionable. For example, Battelle employs an arc efficiency of about 75% for SMAW and 40% for GTAW processes. These results cannot be directly applied to the project as the project results were produced with autogenous welding. The energy required to melt the weld metal in the GTAW process is considerable. It is anticipated that much more of the arc energy is available with the autogenous process used in the project thus making the two processes closer in heat input than other research would indicate.

A method currently being researched by the writer to correlate the arc energy of the two processes is by simple calorimic evaluation. With this method, a small length of steel bar is heavily insulated and its temperature monitored at its core by an embedded thermocouple. Several runs with similar currents will be conducted on the bar with the GTAW and SMAW processes. With use of the relationship:

$$\Delta H = m \cdot C_p \cdot (T_2 - T_1)$$

the relative efficiency of the two processes can be established.

A significant problem encountered during pipe section welding was continuously increasing pressure within the pipe section. The pipe section had a volume of only about 1.23 liters. This volume is considered too small for further testing as the volume expansion of the coolants was found to be very significant. It was difficult to control the internal pressure with the regulator employed in testing and inaccuracies were surely inherent with the method of reading the gauge and recording it on the strip chart. A larger pipe section will be necessary and a more sophisticated pressure control or a gas over liquid accumulator will be needed for future testing and research.

The optical pyrometer used in the experiments did have limitations as such a large focal spot size made it difficult to achieve successful runs with acceptable output. A small spot pyrometer will be needed for future work. However, the advantages of optical pyrometry over other weld cooling rate methods such as thermocouple plunging were clear. If the spot was on target, reliable results were produced. EWI research reported significant problems with thermocouple scatter and failures. In proper fairness to the EWI research, optical pyrometry could not be used with their work due to the large volumes of gasses produced by the SMAW process.

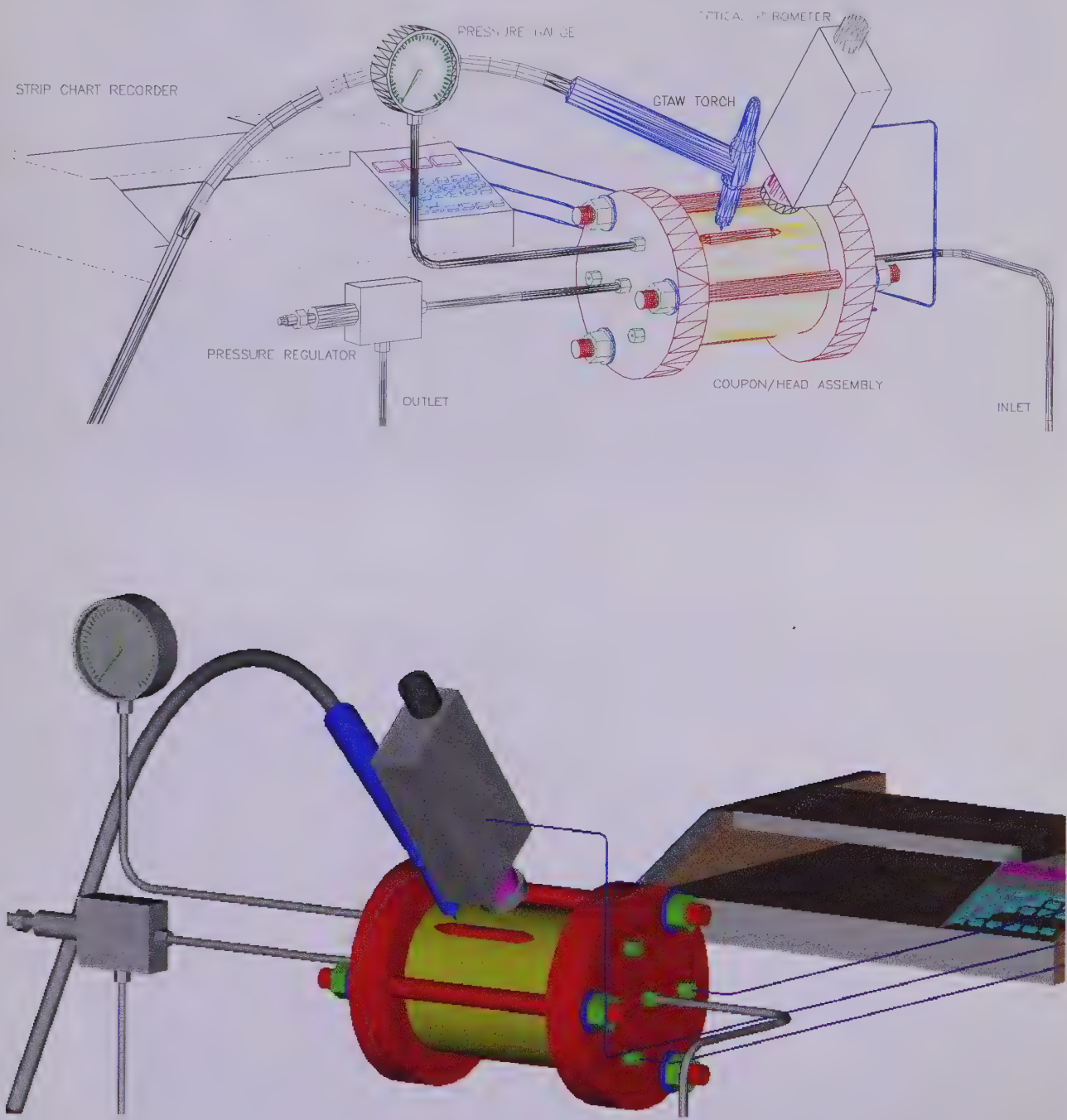
In general, the pressurized pipe section assembly functioned very well and the thin thermocouple wire used to monitor I.D. temperatures exhibited excellent response. With increased to the pipe section size, more dependable pressure control devices, and a better optical pyrometer, the method will prove a valuable tool for pipe section cooling rate control.

7.0 Conclusions

1. With water as a coolant, the temperature at the I.D. of a pipe section could be increased by increasing the pipe pressure. The temperature was found to follow very close to T_{sat} except at low pressures with fairly high heat inputs where indications of boiling transition were observed. At elevated pressures, no sign of transition from nucleate to film boiling was observed even at very high heat inputs.
2. The weld cooling rate could not be controlled with water as a coolant. The increased volume of heated metal promoted by elevated pipe I.D. temperature was ineffective in slowing the cooling rate.
3. When water is mixed with liquids possessing lower T_{sat} than the T_{sat} of water, the response of the pipe I.D. temperature is still to follow very close to that response of pure water. At low pressures, the mixture exhibited a higher propensity for transitional and film boiling.
4. When water is mixed with liquids possessing higher T_{sat} than the T_{sat} of water, the pipe I.D. temperature reaches a temperature somewhere between the T_{sat} for water and the higher T_{sat} liquid. If the higher T_{sat} liquid possesses a thermal conductivity low enough, cooling rate will be reduced. This conclusion is based on the I.D. temperature response with a 50% ethylene glycol/water solution.
5. The method discussed and the use of glycol/water solutions represents a practical method of controlling cooling rates in pressurized pipe sections providing acceptable correlation between SMAW and autogenous GTAW can be established.

8.0 Figures

FIGURE 1
BOILING SUPPRESSION TEST APPARATUS



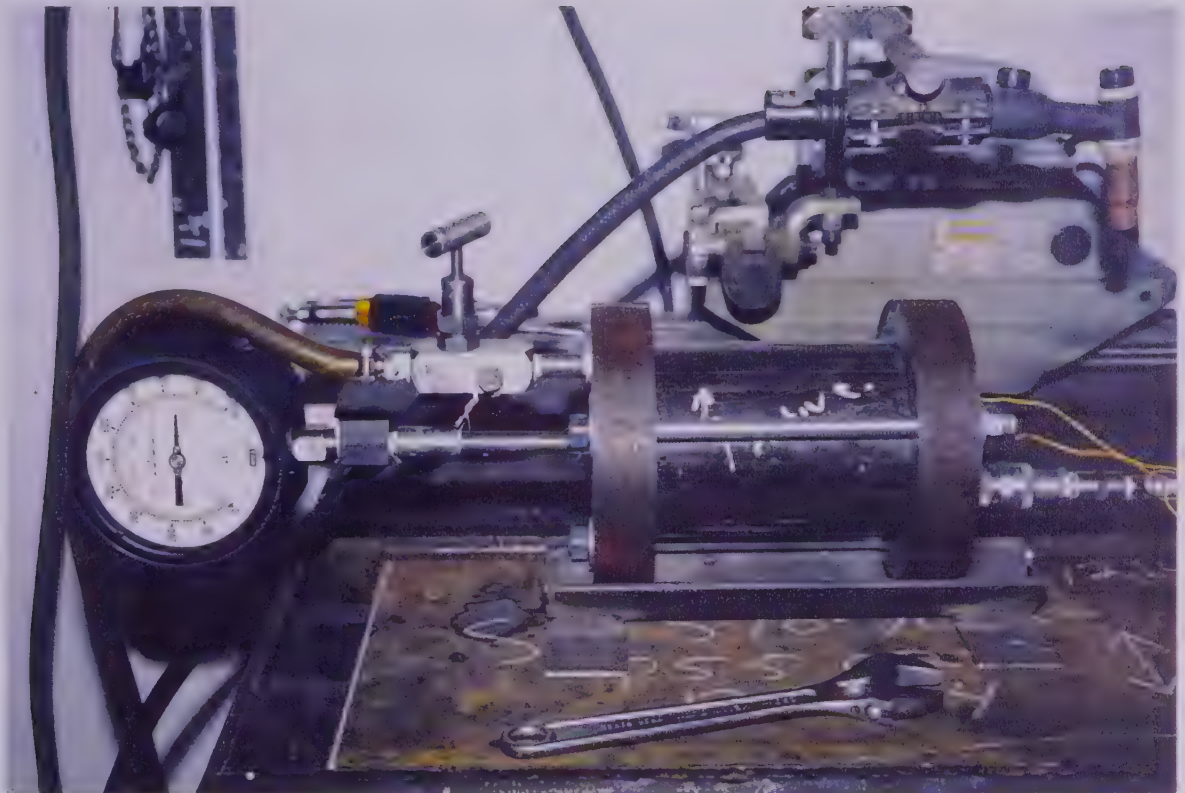


Figure No. 2
GTAW Torch and Cutter Crawler Assembly
Pipe Section in Assembly in Foreground

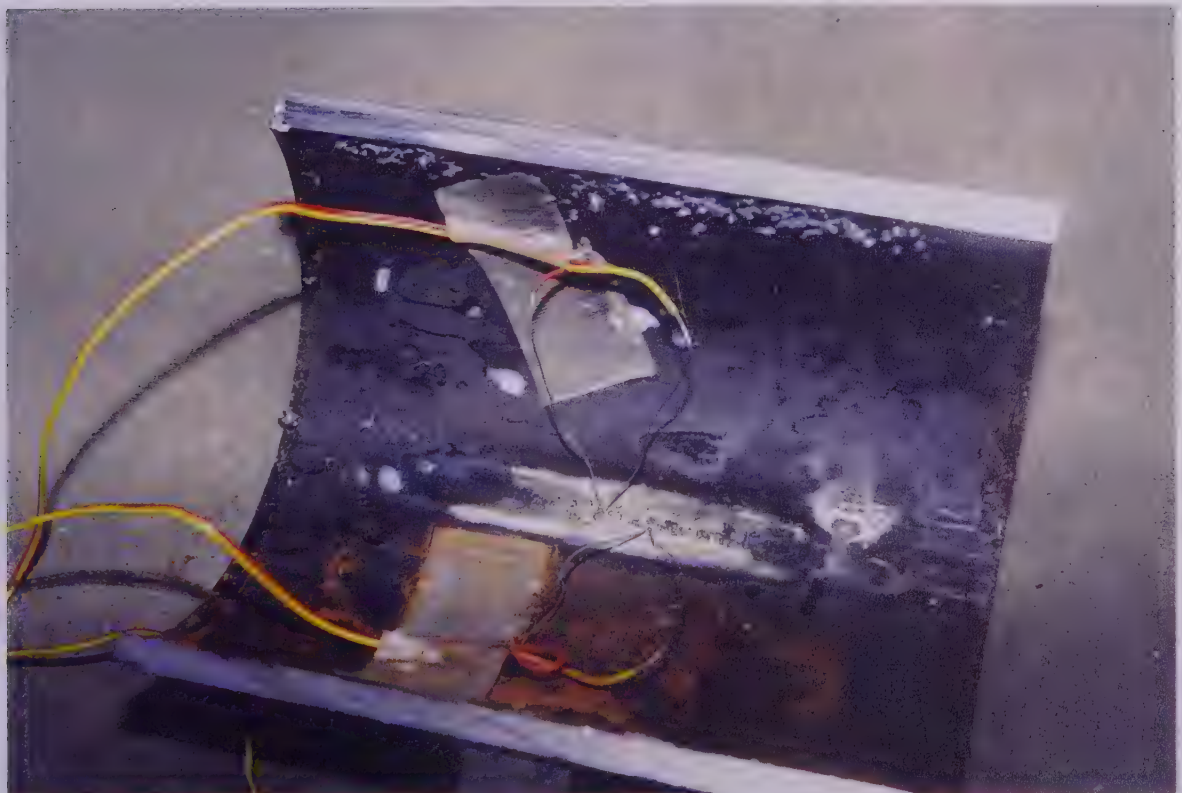


Figure No. 3
I.D. View of Longitudinally Sectioned Pipe Coupon
Note: Location Thermocouple Locations Relative to the Heat Discolored Zone

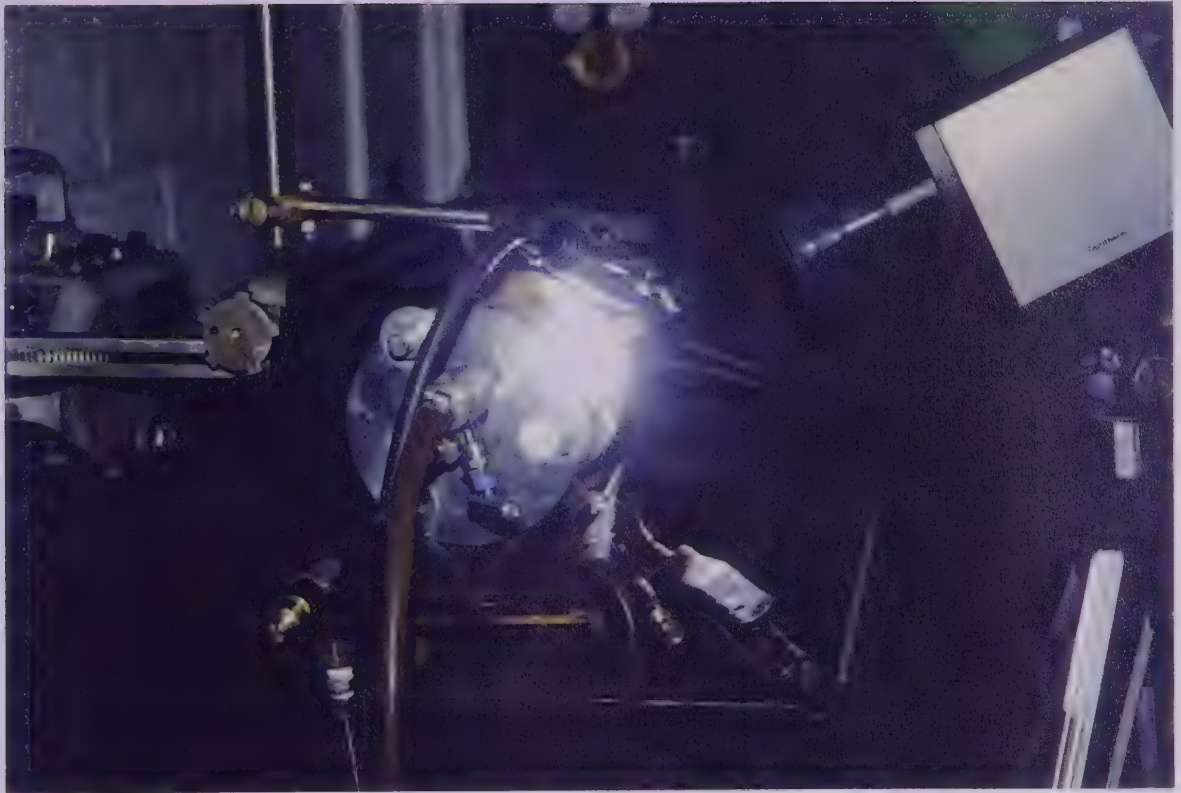
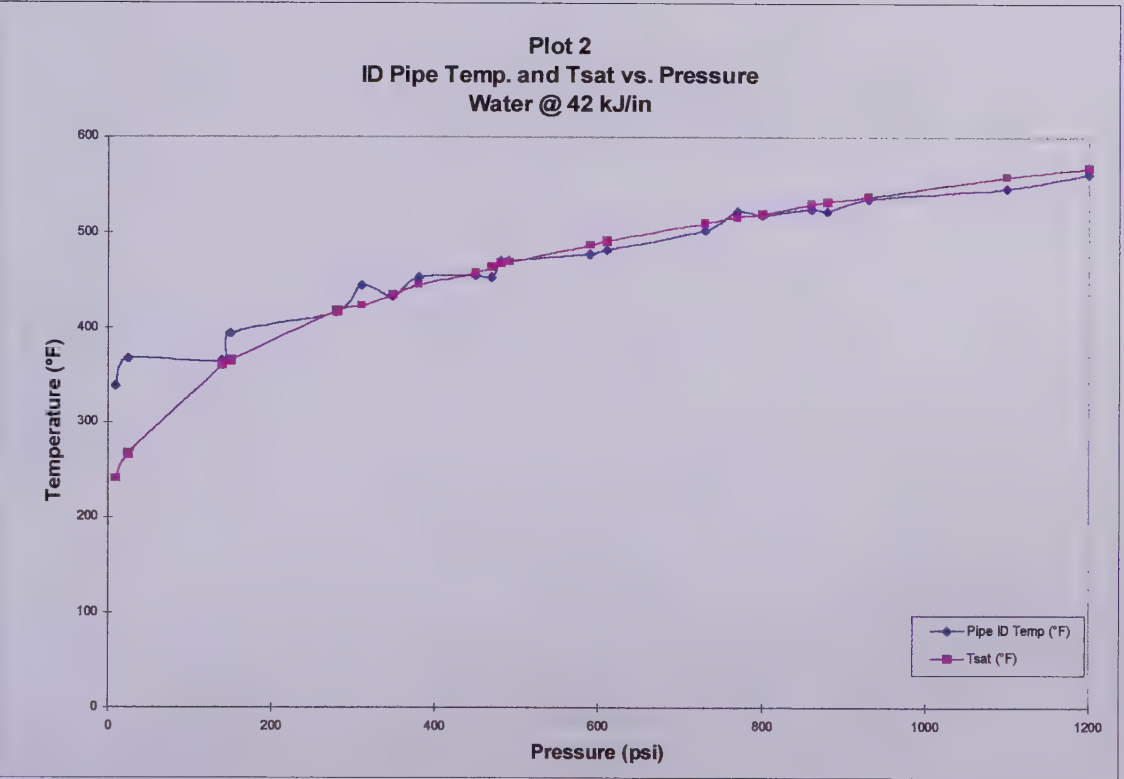
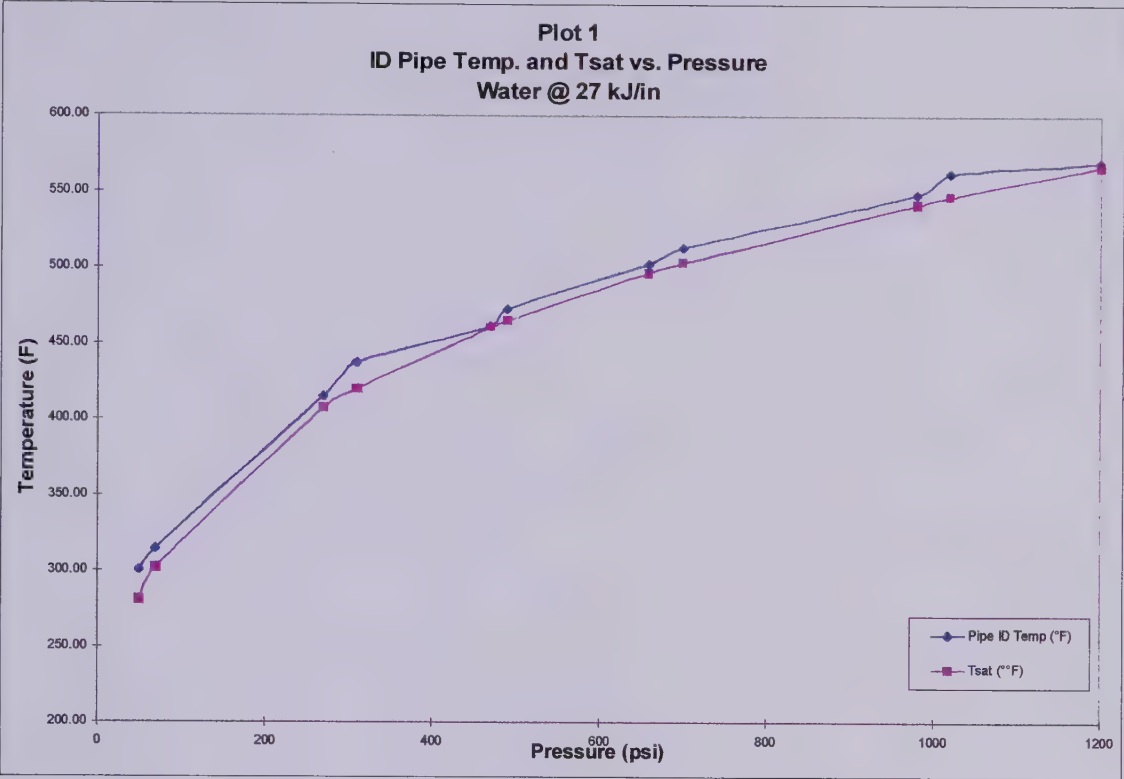


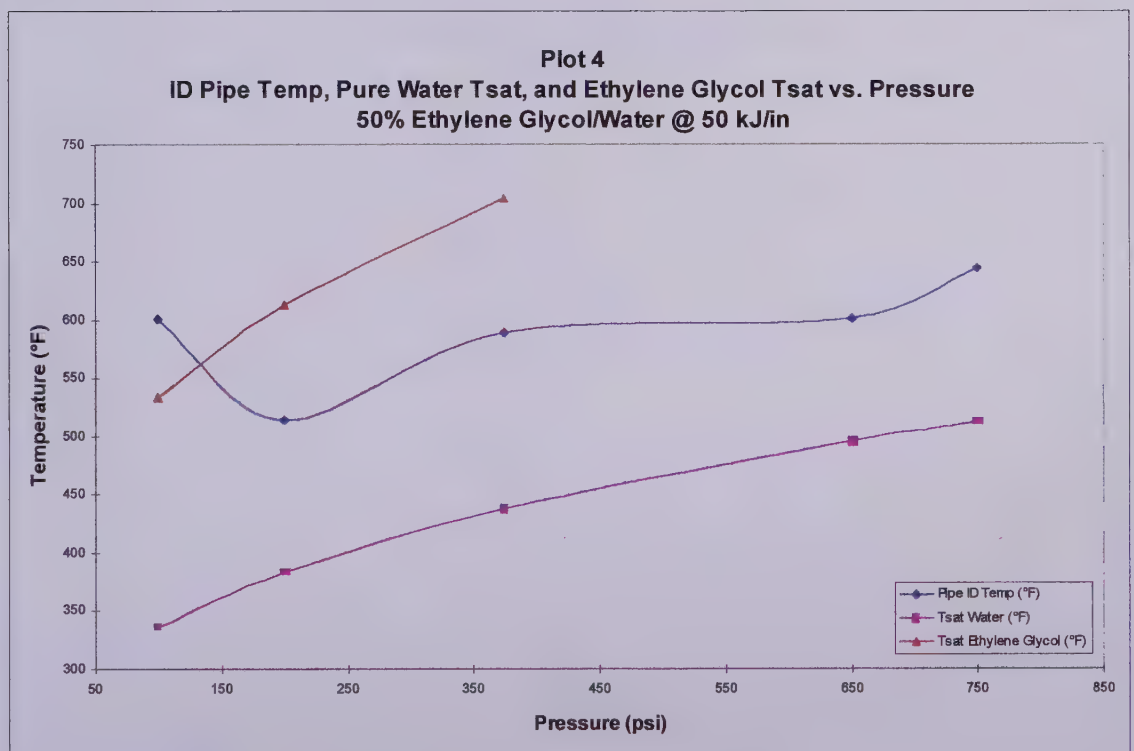
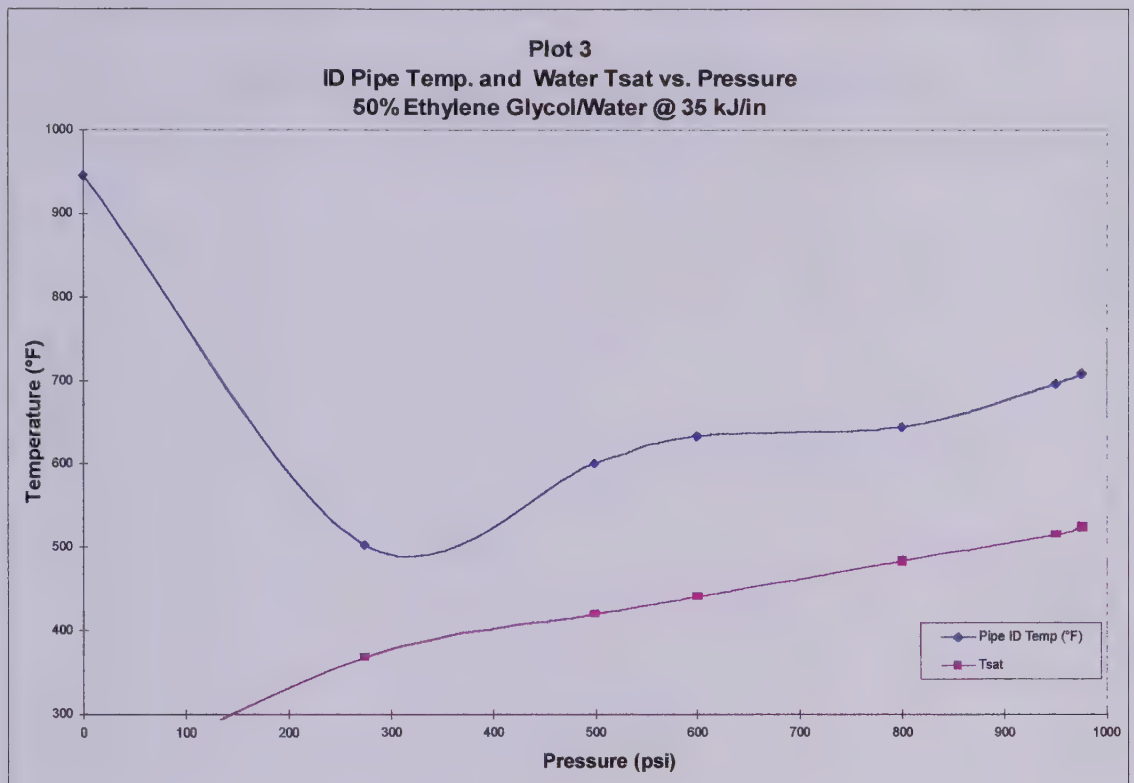
Figure No. 4
Pipe Section During Welding
Note: O.D. Temperature being Monitored by Optical Pyrometer

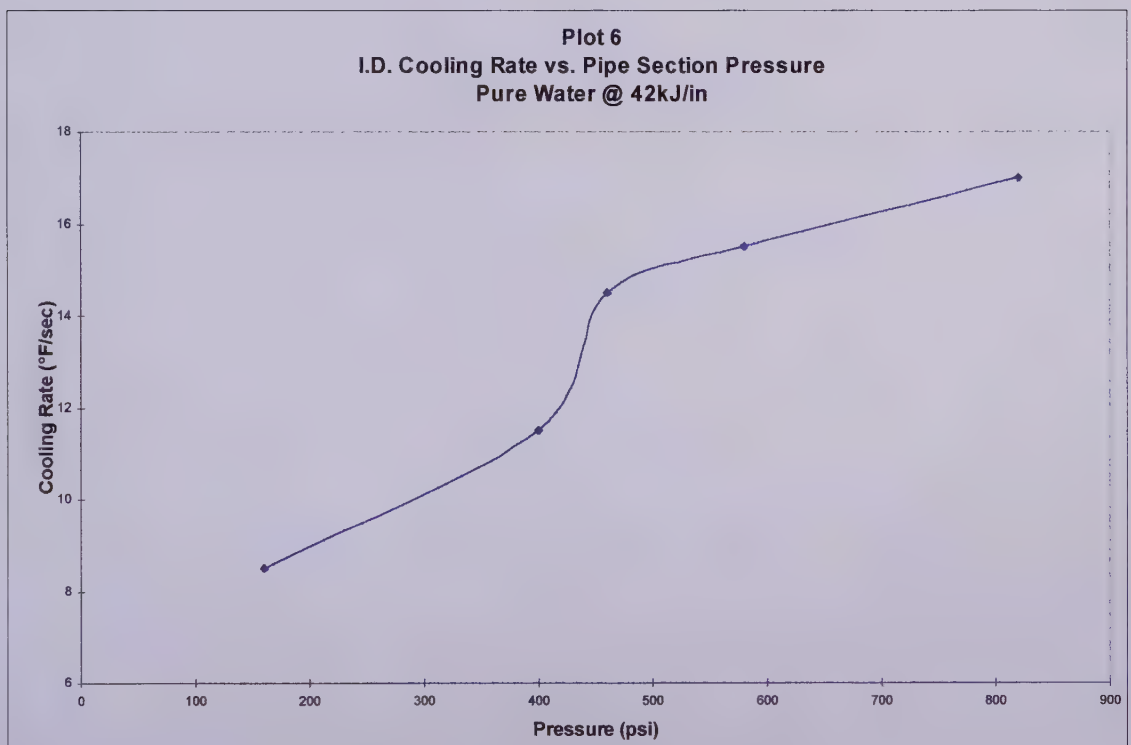
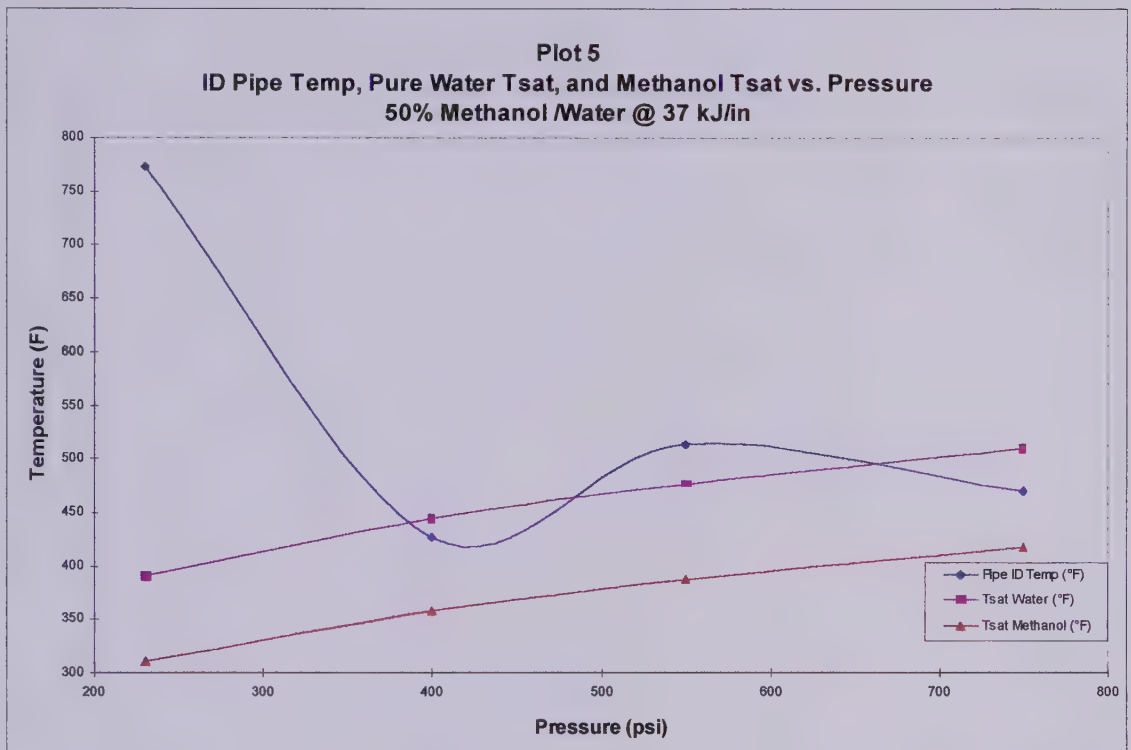


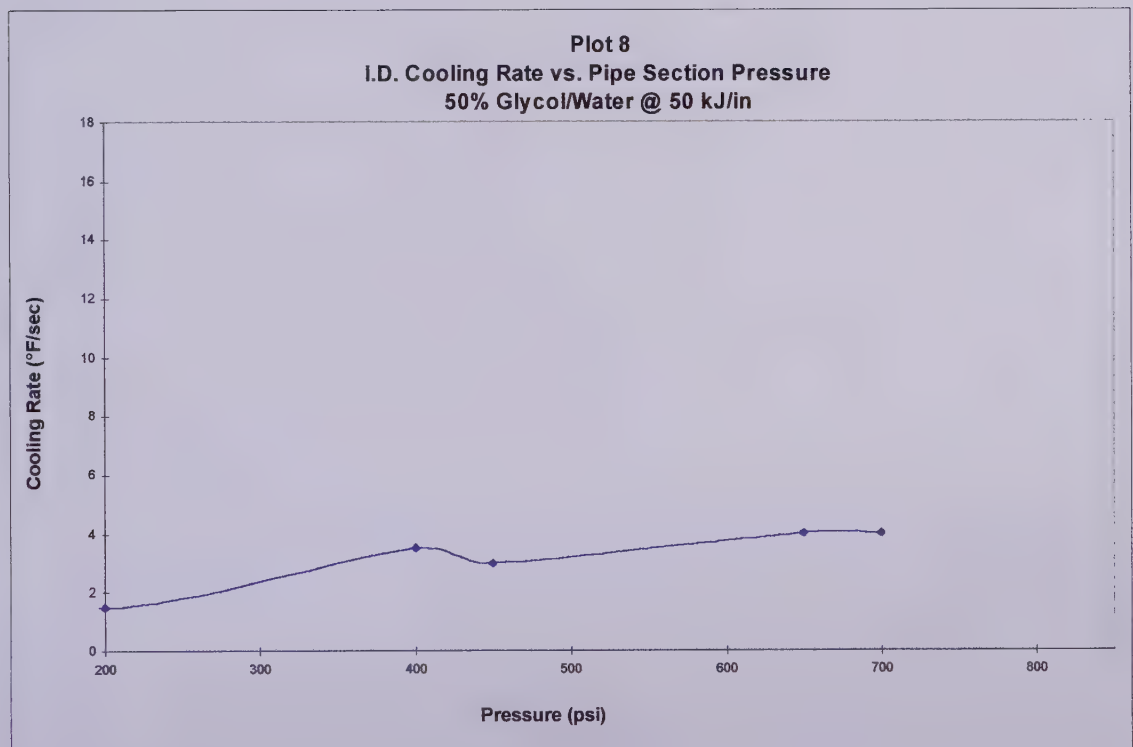
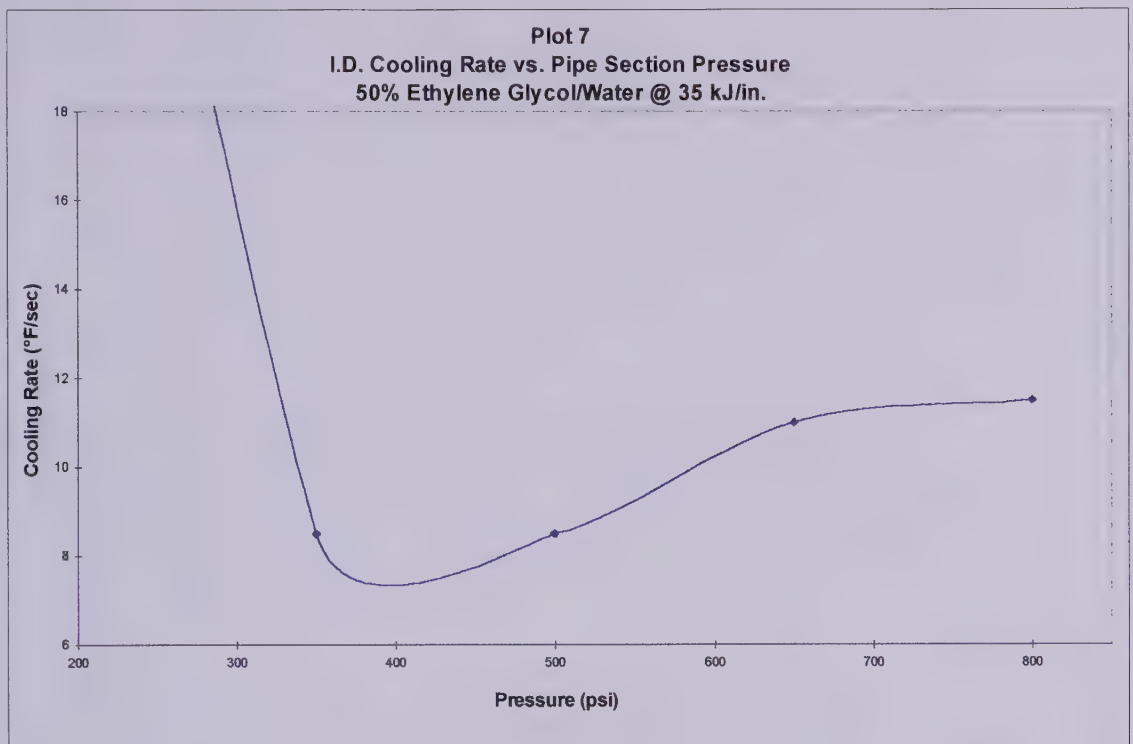
Figure No. 5
Laboratory Technicians(Patrick and Kiara)

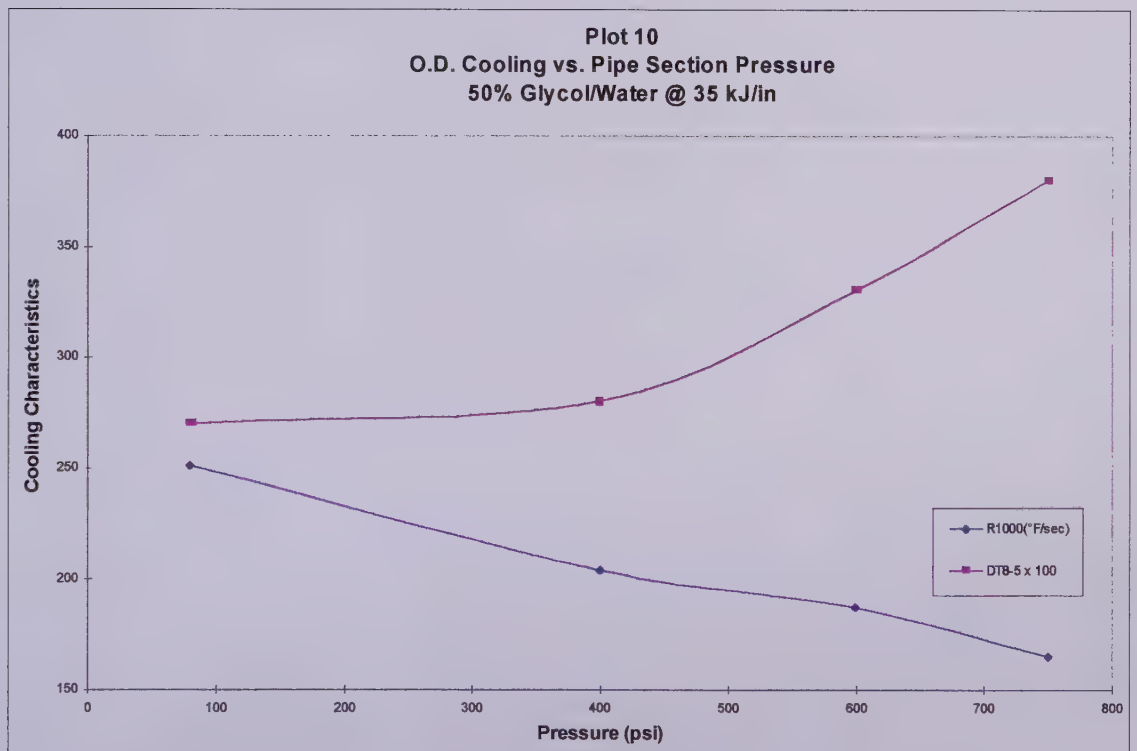
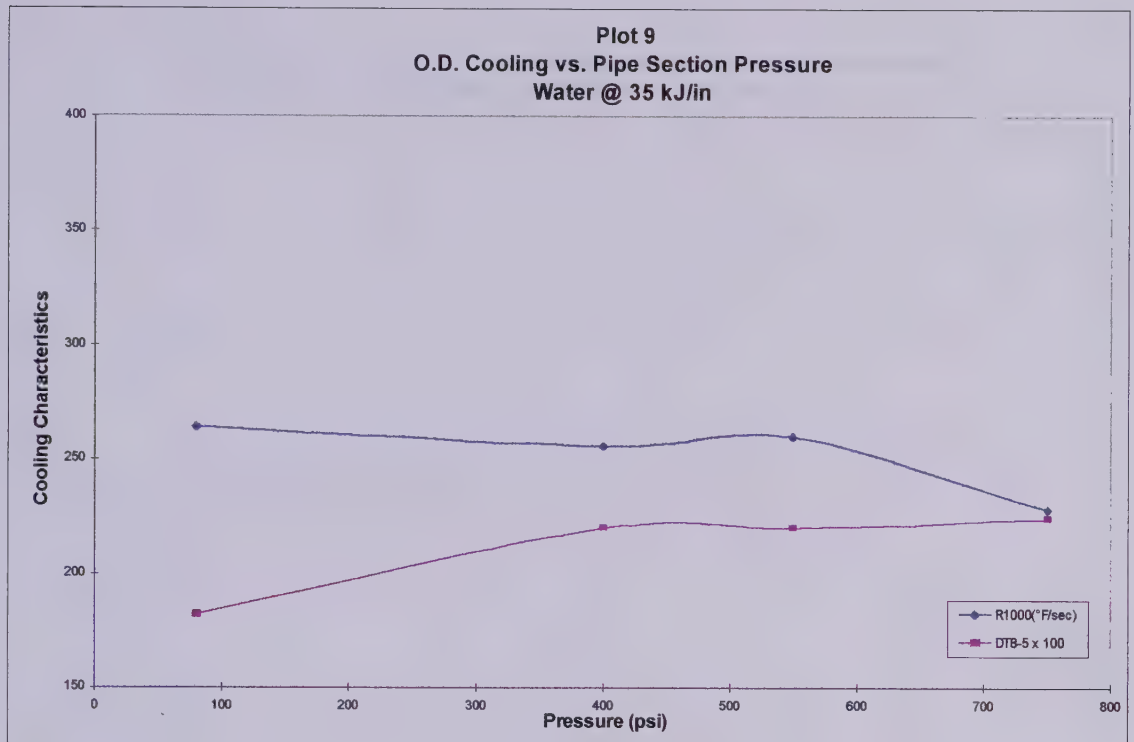
9.0 Plots

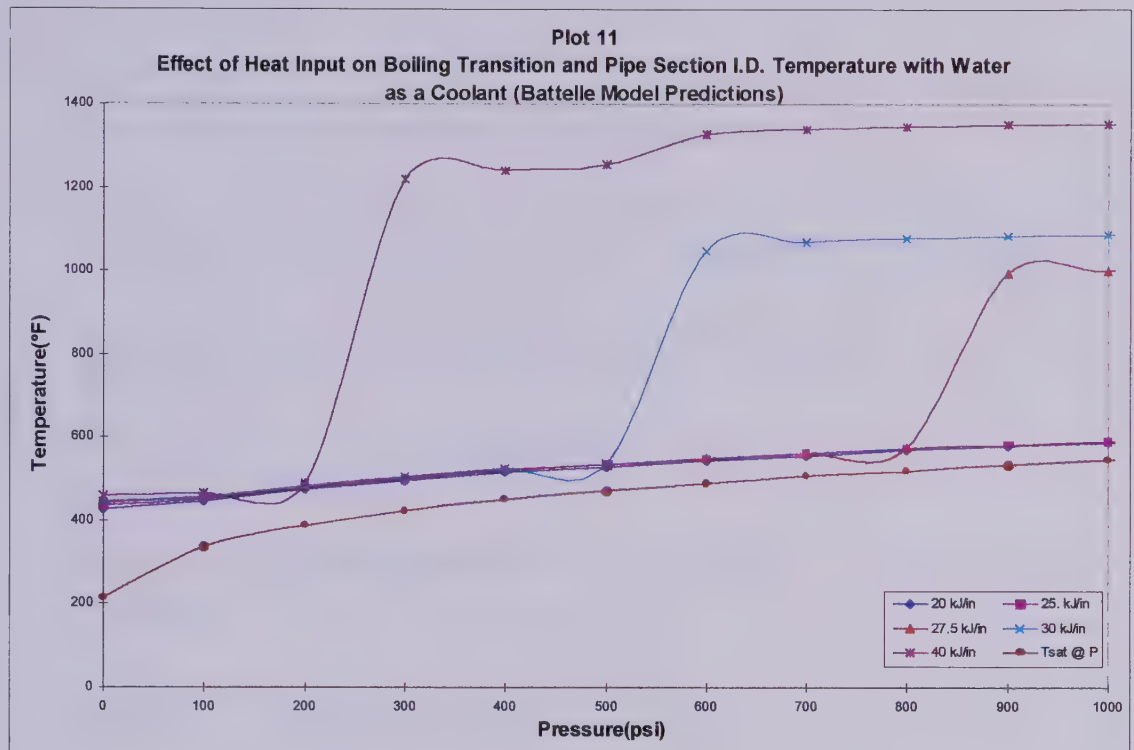












10.0 References

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7. Gallant W.R., "**Physical Properties of Hydrocarbons,**" Gulf Publishing Company, 1973
8. Edison Welding Institute Final Report PR-185-815*, "**Criteria for Hot Tap Welding Further Studies,**" 1989

11.0 Appendix A

PM 9920/00

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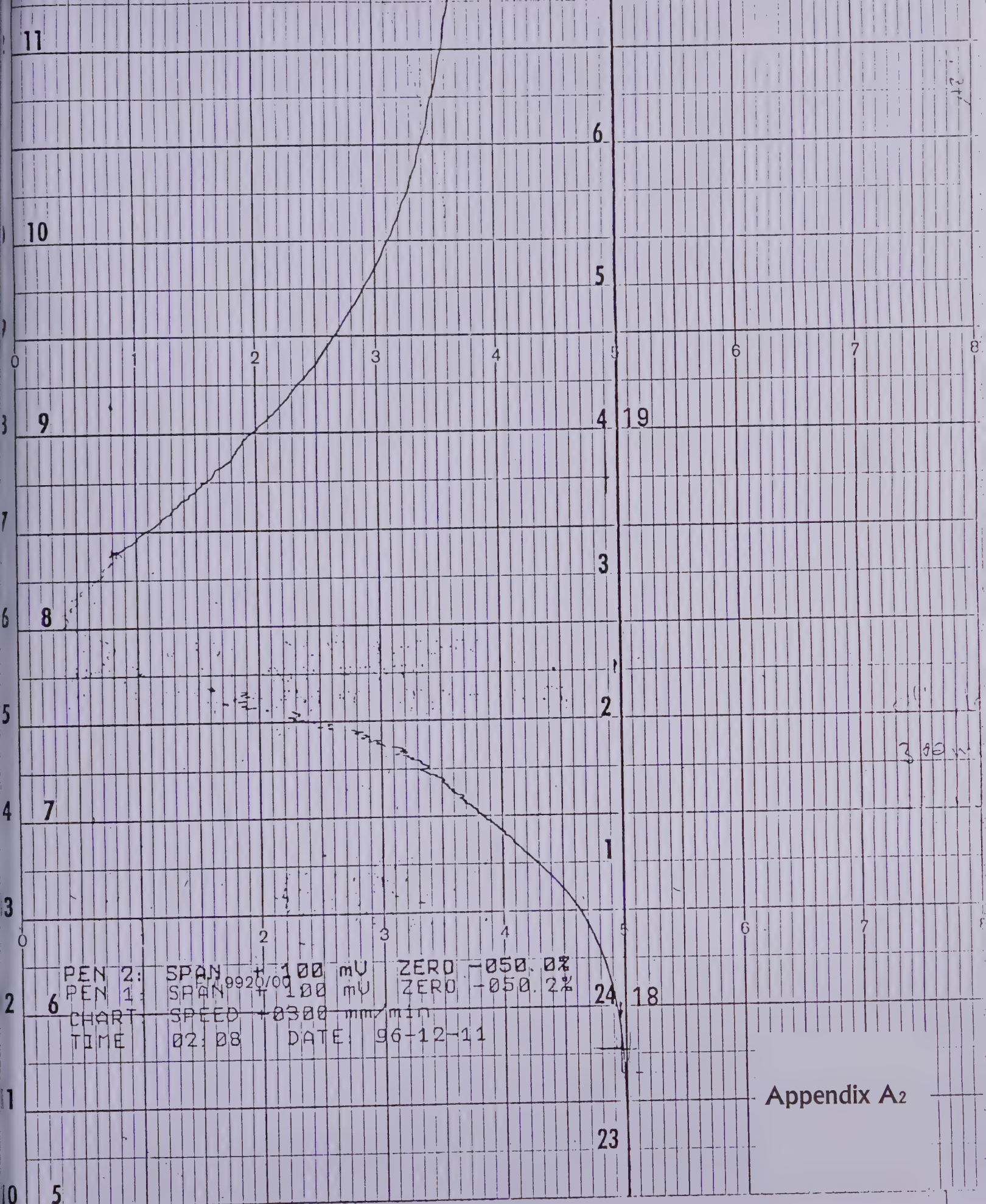
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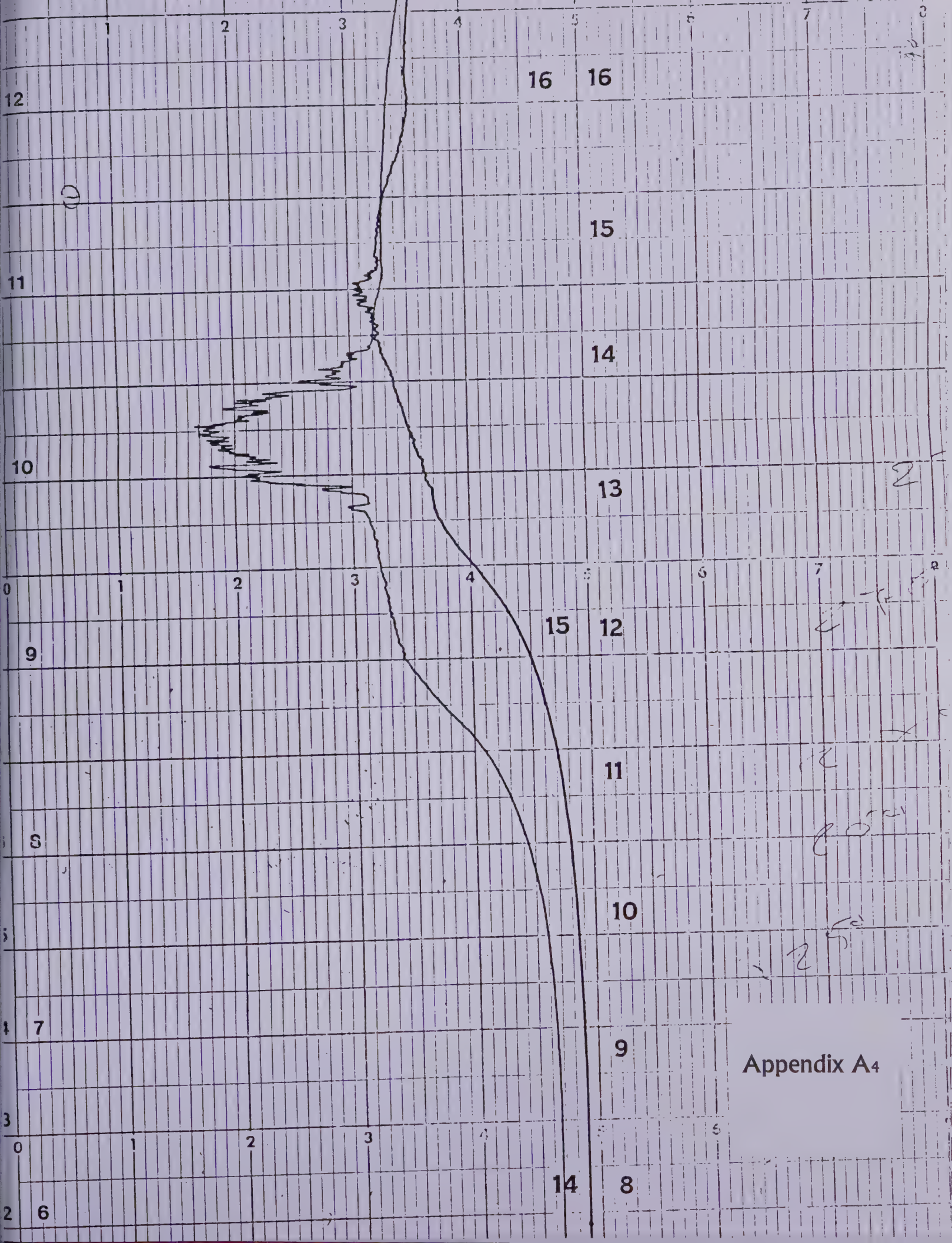
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25 mV SEC.
300 mV/μ

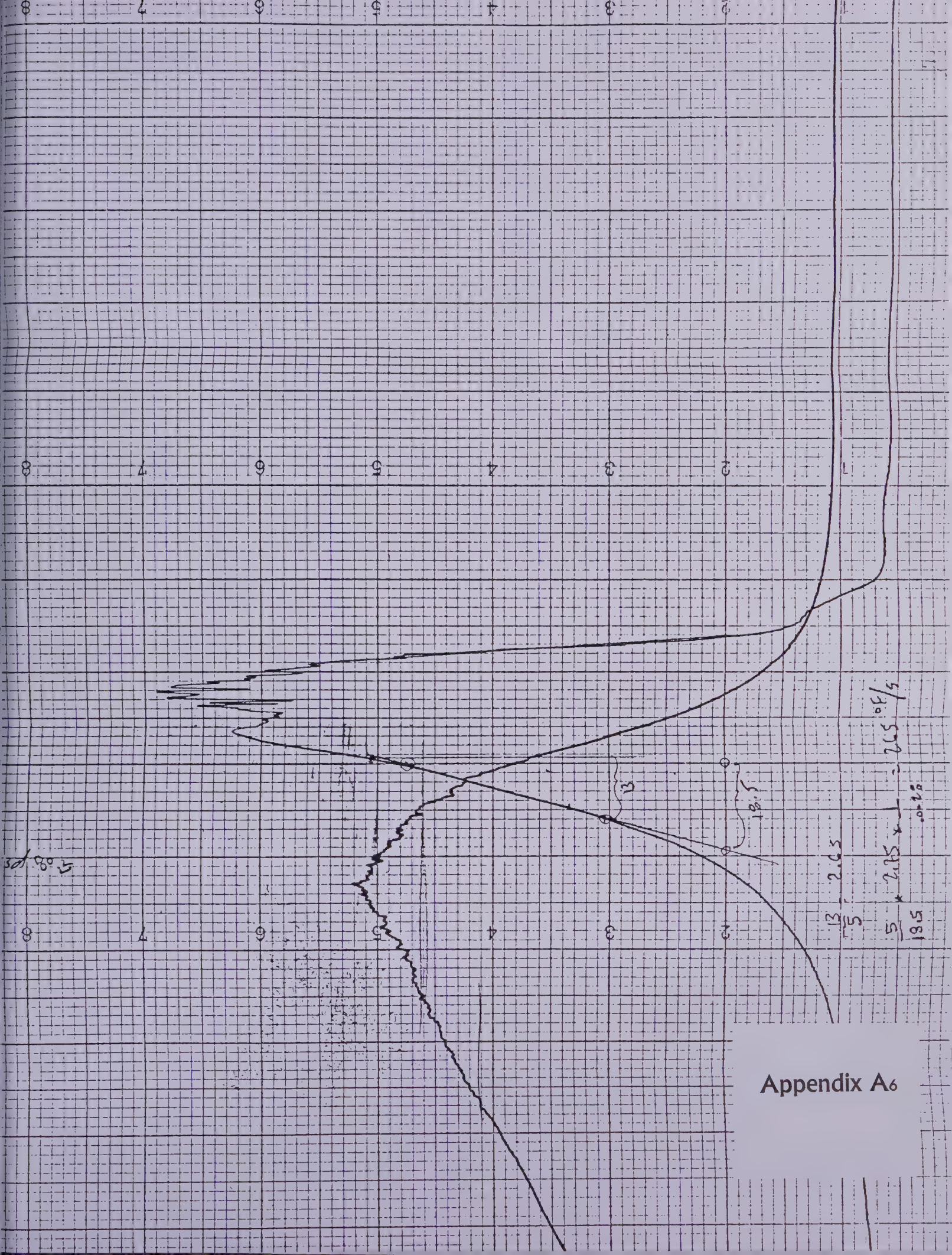
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PEN 1: SPAN + 25 mV ZERO -050.2%
CHART: SPEED +0300 mm/min
TIME 02:03 DATE: 96-12-11

Appendix A1



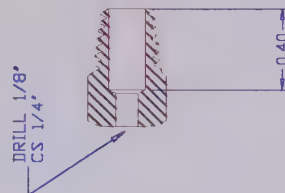
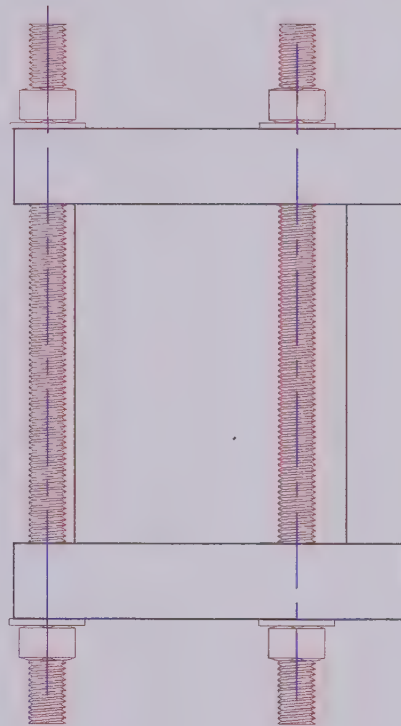
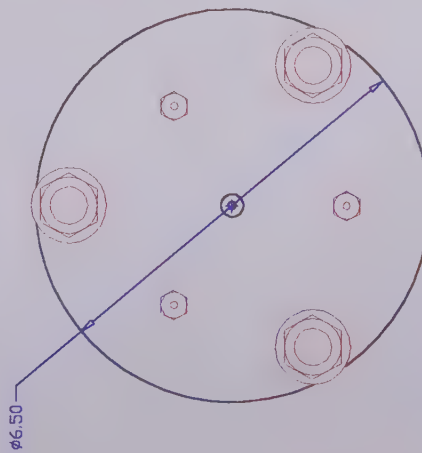
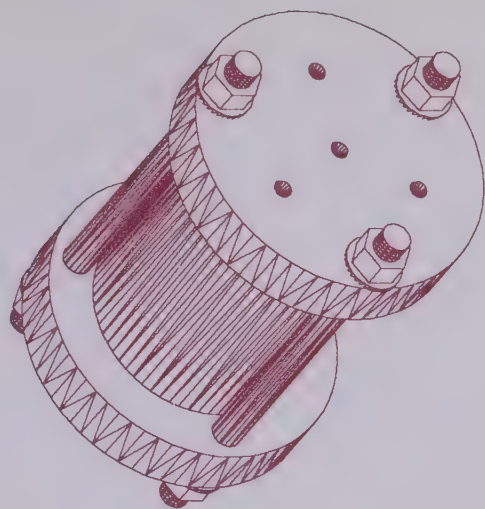
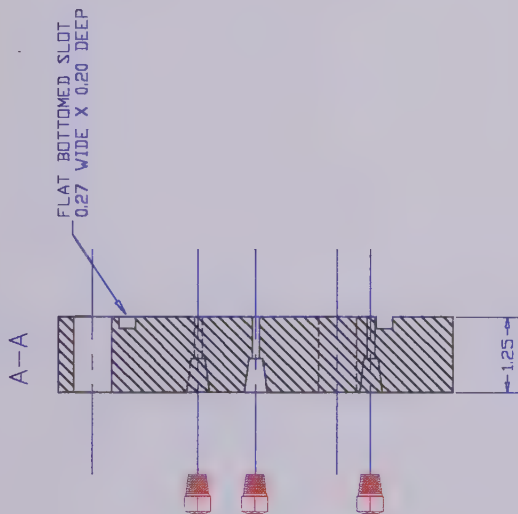
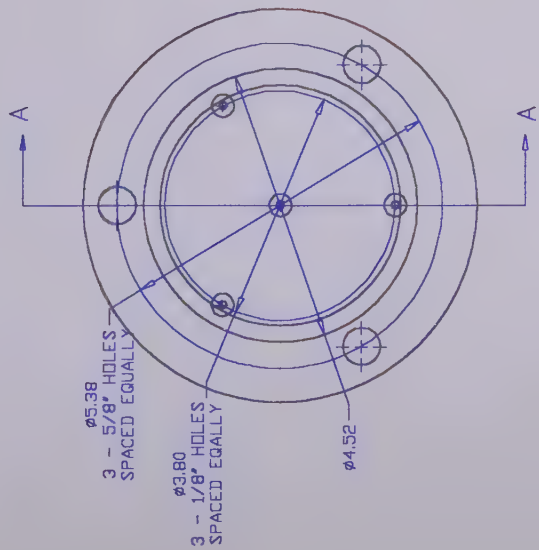
Appendix A2





Appendix A6

12.0 Appendix B



MATERIAL LIST		
ITEM	QTY.	DESCRIPTION MATERIAL
1	1	COUPON SA 106 Gr. B
2	1	COUPON SA 333 Gr. 6
3	2	HEADS SAE 4130 Q&T 18-22 HRC
4	3	5/8" TRD. ROD SAE Gr. 5
5	6	5/8" NUTS SAE Gr. 5
6	6	5/8" WASHERS HARDENED

NOTES:

1. USE 0.5 mm BEHN IMPREGNATED GASKET MATERIAL FOR END GASKETS
2. TORQUE HEAD BOLTS TO 60 FT. LBS.
3. MAMP 1000 psi
4. ONLY TO BE USED WITH LIQUID FILLED PIPE COUPONS

PRESSURE COUPON

DRAWN BY: RORY BELANGER DATE: 8/7/03/23 SCALE

CHECKED BY: SAME DATE

PART NUMBER REVISION

SHEET 1 OF 1

